Analysis of Thermal Plants Configuration

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Abstract Initially some thermodynamic concepts are presented aimed at a synthesis of different conceptions of thermal cycle engines. The Rankine cycle and its major components are related to the concepts previously discussed. Some operational aspects of boilers, steam turbines, condensers and cooling towers, are emphasized. The Brayton and the combined cycles are presented with emphasis on the recovery boiler.

1 Introduction

The majority of the existent thermal plants still relies on the heat produced by combustion reactions and its fuels such as, pulverized coal, natural gas or fuel oil have been used for more than one century.

Besides those fossil thermal plants are the nuclear power plants. There, the heat comes from a fission nuclear reaction. In any case the thermal plant operation may be summarized by the classical diagram presented in Fig. 1.

The temperatures of the heat source and sink are crucial parameters to establish the theoretical maximum efficiency, obtainable for any thermal engine operating between these two Thermal Energy Reservoirs (TER).

The relationship between the maximum efficiency and the temperatures is the well known equation, the Carnot thermal efficiency, based on the second law of thermodynamics,

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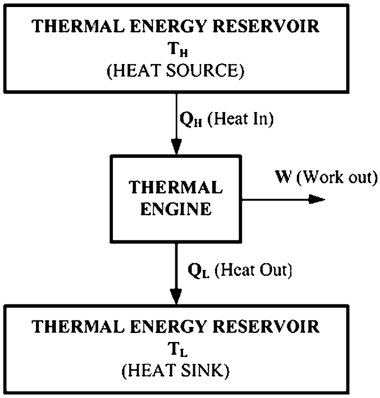


Fig. 1 Energy flow

$$\eta_{\max} = 1 - \frac{T_L}{T_H} \tag{1}$$

It is important to emphasize that the temperatures T_H and T_L are temperatures of the TERs and not of the working fluids. These fluids have varying temperatures, flowing inside the thermal engines while exchanging heat with the thermal reservoirs.

The lower temperature of the thermal reservoirs is a characteristic parameter of the atmosphere, of a river or the ocean, usual heat sinks. This temperature is an uncontrollable variable, that might be considered nearly a constant for the purpose of this introductory analysis.

A simplified expression for the heat rate, rejected by the thermal engine, $\dot{Q}_L$, is

$$\dot{Q}_L = UAf\left(\bar{T}_f - T_L\right) \tag{2}$$

where U is the averaged global heat transfer coefficient and A the required heat transfer surface.

f is a monotonous crescent function upon the temperature difference $\left(\bar{T}_f - T_L\right)$. The fluid averaged temperature $\bar{T}_f$ could be interpreted as representative of the fluid thermal process, when crossing the equipment (part of the thermal engine) where the heat is rejected to the lower temperature heat reservoir.

The Eq. 2 implies that if U is nearly a constant, smaller the temperature difference $\left(\bar{T}_f - T_L\right)$, greater the required area A, and the cost of the equipment where the heat is rejected. Alternatively greater the temperature difference more economical the heat exchanger. The increase in this difference is practically obtained increasing $\bar{T}_f$ instead of lowering T_L. And this higher $\bar{T}_f$ can be associated to a cycle with a lower maximum theoretical efficiency. In this case the temperature of the low TER will be greater than the one associated with T_L and the Eq. 1 can be used to evaluate this reduction.

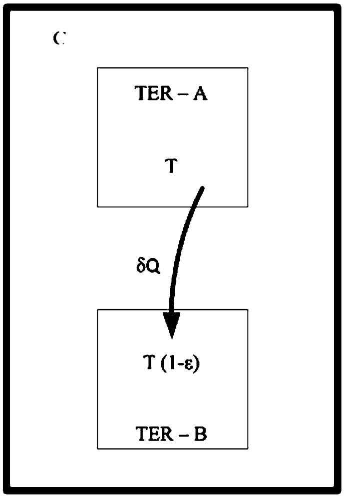


Fig. 2 Two TERs exchanging heat

A more quantitative way to show how a heat transfer with small temperature difference is more efficient is analyzing de heat transfer itself as in Reynolds [1].

Let A and B two TERs exchanging heat. C an isolated system containing only A and B as shown in Fig. 2.

The entropy variation for the system C, can be written according to Eq. 3

$$dS_C = d(S_A + S_B) \geq 0 \tag{3}$$

For the two TERs,

$$dS_A = -\frac{dQ}{T} \tag{4}$$

$$dS_B = \frac{dQ}{T(1-\varepsilon)} = \frac{dQ}{T}\left(1 + \varepsilon + \varepsilon^2 + \ldots\ldots\right) \tag{5}$$

Adding we have,

$$dS_C = \varepsilon\frac{dQ}{T} + \ldots \geq 0 \tag{6}$$

So the only way to have a reversible heat exchange is $\varepsilon \to 0$ meaning a temperature difference infinitesimal. In other words, greater the temperature difference more energy destruction, more irreversible the process and consequently less efficient.

The high temperature thermal reservoir is a model more complex to be established. The more frequent heat source, in thermal plants is the combustion reaction. It is present in pulverized coal boilers, natural gas boilers, combustion chambers in gas turbines or inside the diesel engine cylinders.

This oxidizing reaction, highly exothermic, occurs in a relative very short time if compared with the necessary time for the heat flow to be established. This results in very high temperatures for the gases that are products of this chemical reaction.

The previous discussion indicates that the temperature of the working fluid has to be as high as possible to increase the thermodynamic efficiency and to minimize the entropy increase.

After this brief introduction it will be shown how those concepts play an essential role in the thermal plants configuration.

2 External and Internal Combustion Engines

In the external combustion engine the working fluid does not participate of the combustion reaction and it is also called closed system. The most important example of this kind of engine is the Rankine cycle, the model for the steam power plant. In this case the combustion takes place in a boiler where the heat generated by the combustion is used to generate steam. There is also the heat produced in a nuclear reactor and transferred to steam generators through pressurized water.

Two variations of the Rankine Cycle are; the Kalina Cycle where the working fluid is a mixture of water and ammonia and the Organic Rankine Cycle where some special organic fluid is specified to use waste heat.

There are other examples of external combustion engines such as the Stirling and Ericsson cycles.

In the internal combustion engines, called open cycles, the air is the working fluid at least until it mixes with the fuel and undergoes the combustion. The main open cycles used in power plants are the Brayton cycle (gas turbines), Diesel and Otto cycles (reciprocating motors).

This open configuration is based on a different thermodynamic concept. In the closed system there is a unique working fluid that exchange only heat and mechanical work with the exterior. In the open configuration at its turn, there is an exchange of mechanical work, an inflow of air and fuel and an outflow of gases products of the combustion.

Although there is no heat input, we may still consider this internal combustion engine, a thermal engine. The combustion process can be seen as a transformation of internal chemical energy into internal thermal energy, in the same way a heat exchanger would do.

Regarding the heat outflow, in the Diesel and Otto engines a significant amount of heat is rejected to a cooling water, that circulates inside the engine, mainly to maintain the mechanical integrity of engine parts. The thermodynamic and mass closures necessary to maintain any engine operating steadily is done by the atmosphere, receiving the gases and renewing the air supply, and the refuel completes the “cycle”, in a broad sense.

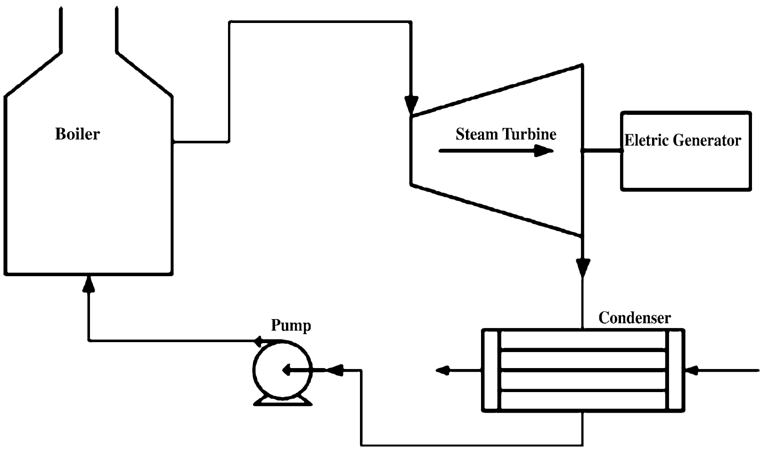


Fig. 3 The basic Rankine cycle

3 The Rankine Cycle

The basic components of the Rankine cycle are:

- Boiler or Steam Generator
- Turbine/Electric Generator
- Condenser
- Pumps

Those equipments, are interconnected as the diagram in Fig. 3 indicates.

Due the objective of this analysis, restricted to industrial power plants, we shall discuss the main components (equipments) related to this application of the Rankine cycle.

3.1 Boilers

The industrial power boilers are large and complex heat exchange equipments that are able to provide steam at high pressures and also at large flow rates.

Usually, those boilers are water tube boilers, i.e. the water flows inside several small tubes. One of the reasons is a substantial increase in the heat exchange area this will helps to control the irreversibility in the heat transfer as mentioned before.

For water the critical pressure and temperature are equal to 22,064 MPa (3,200 psia or 218 atm) and 374°C (705°F), respectively. There are boilers operating at pressures of 31 MPa and temperatures around 600°C. Those boilers are called Supercritical Boilers although the last noun might be considered inappropriate due the fact that above the critical pressure there is no boiling.

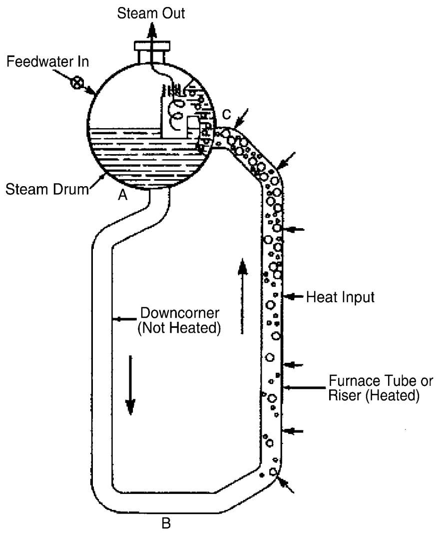


Fig. 4 Thermal circulation loop [2]

The present steam flow rate upper limit, for this kind of boiler, is around 1,300 kg/s.

One important distinction among several industrial power boiler configurations is whether exists or not a separation point between the region where the vapor is produced and the other, where the steam is just superheated.

The boilers which the separation point does not exist are called Once-Through Steam Generators (OTSG) in contrast with boilers that have a drum to separate the liquid water and steam. Figure 4 illustrates this last configuration.

The Rankine Cycle demands for high saturation temperatures for the working fluid when it crosses the steam generators. This is especially true for those which the heat source consist of the burning of fossil fuels. This need was always difficult to be fulfilled using drums.

This boiler component is a pressure vessel subjected to strong thermal and mechanical loads. Figure 5 shows this critical component.

Since the beginning of the boiler industry an alternative to this conception was sought and the OTSGs were developed in this context. In those boilers we may say, that during normal operation water molecule does not pass twice for any cross section of the water tubes or there is no water recirculation. The sketch in Fig. 6 shows a typical once-through circuit of a boiler.

The separator above is designed to remove any moisture present in steam especially in the startup and partial load operations.

These first two concepts can be summarized by saying that due the need for high temperatures/pressures in the Rankine cycle the insertion of the steam drum will become a limitation in the design of high pressure boilers. All supercritical steam generators have this once-through design.

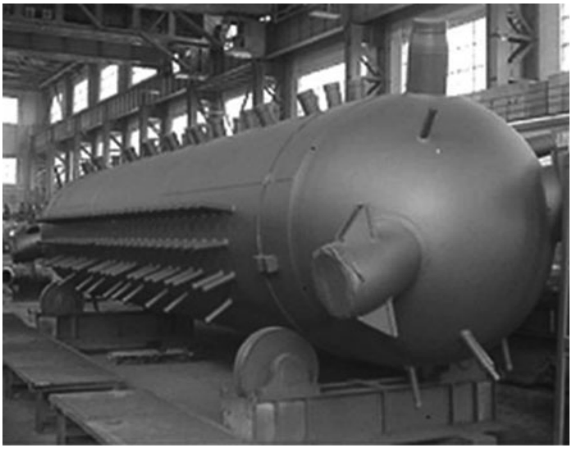


Fig. 5 Steam drum

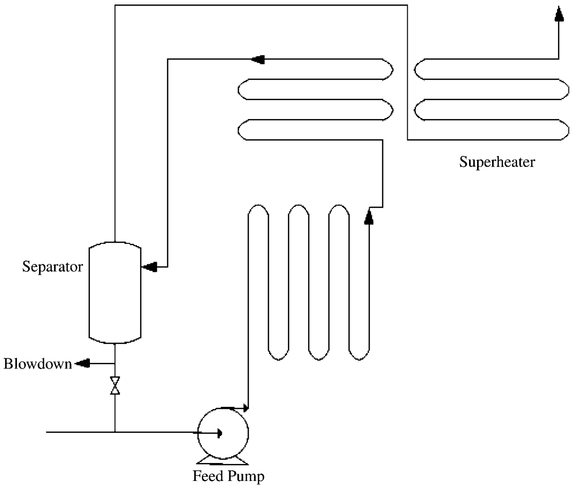


Fig. 6 Once through steam generator water/steam circuit

Another important part of the boilers is the Economizer. There, the liquid water prior entering in the evaporator (boiling region) is preheated using the hot gases after they leave the superheater.

The temperature difference of the liquid water leaving the condenser and the temperature of the flame inside the boiler is the greater possible difference occurring in the cycle. It is then necessary to reduce this difference in order to minimize the irreversibility that would occur if the liquid water enters in the boiler at such low temperature. Two actions are usually taken to achieve this goal:

- Preheat the liquid water using steam extracted from the turbines
- Using the economizer

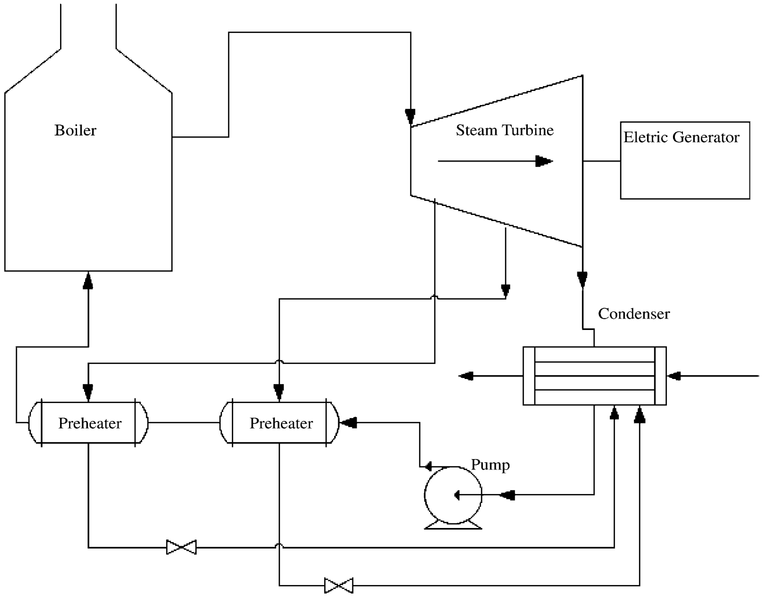


Fig. 7 Rankine cycle with preheating

The cycle in Fig. 7 illustrates the preheating with the steam extracted from the turbines. It is clear that this modification represent an increase in capital costs but the operational cost reduction pays back, even if it is used a larger number of preheaters.

The Economizer is a steam generator internal and the Fig. 8 shows one of its typical location.

Another possibility to increase the boiler efficiency is the insertion of a Reheat section. Looking to this modification from the thermodynamic second law point of view, it will control the irreversibility due to heat transfer. This will be achieved with a smaller temperature difference in the Economizer, between the liquid water and the flue gases. And the thermal energy increase in the reheat section will be internalized in the cycle to be later transformed in useful work at the turbine shaft.

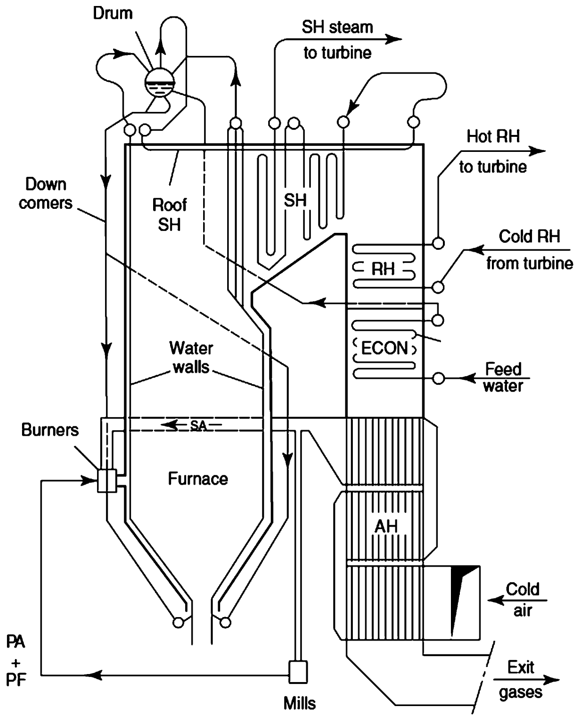
The sketch bellow shows how the search for higher efficiency and less exergy destruction results in some constrains to the steam turbine design (Fig. 9).

3.2 *Steam Turbines*

Steam turbines are very efficient and reliable turbo machines, they convert energy in the form of enthalpy in mechanical work available as shaft torque.

Enthalpy is a function of pressure and temperature for superheated steam, in the Mollier diagram, presented in Fig. 10, is possible to notice that for a higher

Fig. 8 Industrial boiler configuration (boilers for power and process [3]. Legend: *ECON* Economizer, *SH* Superheater, *RH* Reheater, *AH* Air heater, *PA* Primary air, *PF* Pulverized fuel



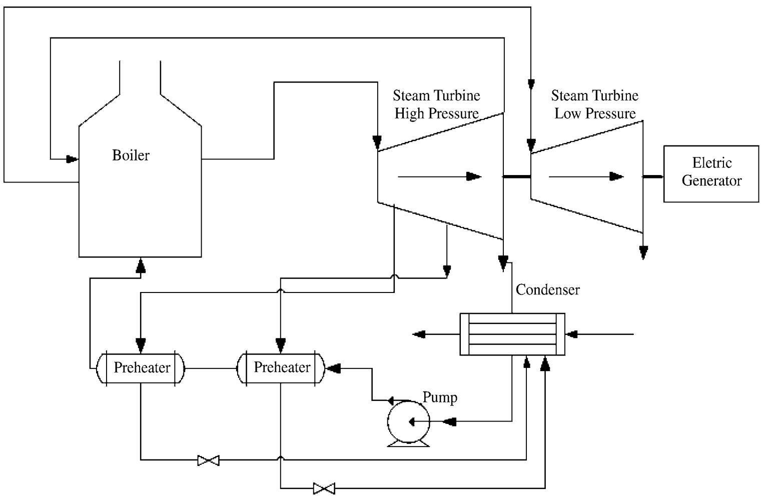


Fig. 9 Rankine cycle with feed water preheat and steam reheat

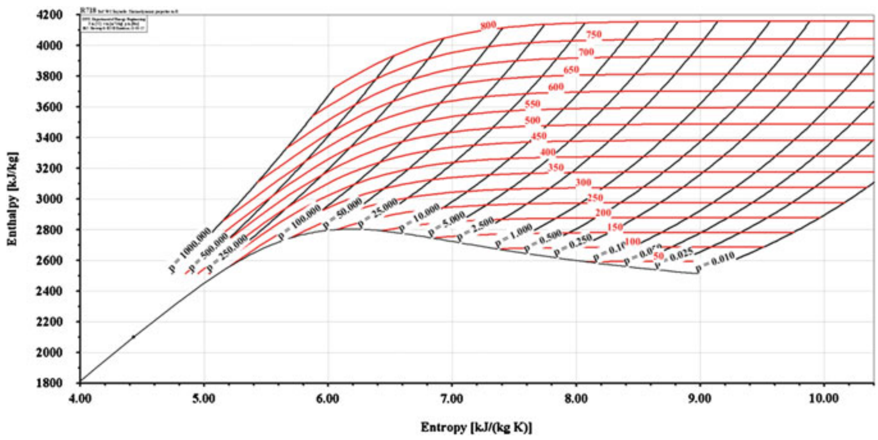


Fig. 10 Mollier chart for water

enthalpy in the turbine inlet it will be necessary high pressures (kPa) and temperatures (°C).

Inside the turbine, enthalpy is converted in kinetic energy through stationary nozzles or by the decrease in the flow cross-sectional area during the flow around the moving blades.

The high speed of the steam, after passing through the nozzles, or the high momentum obtained, will produce an impulsive force on the blade and consequently a torque on the turbine wheel. In this kind of configuration, the impulse stage, the pressure remains constant at least theoretically. Figure 11 shows a Curtis-Rateau turbine. Notice, that in all stages, when the steam flows through the moving blades, the pressure stays constant. This turbine has only impulse blading.

When this momentum variation occurs on the blades, through the area reduction the reaction of the blade's wall will also produce a torque on the wheel. In this case we will have a reaction blade, where the expansion occurs simultaneously to the torque production. Figure 12 shows a turbine, Curtis-Parson, with an impulse stage following the reaction stages.

Steam turbines that produce more than 60 MW usually have more than one cylinder. Figure 13 illustrates those turbines, called compound.

Those diagrams do not show the extraction nozzles but they are present in all configurations and they are usually located in the high pressure turbine.

3.3 Condenser

This heat exchanger operates with the exhaust steam at vacuum. And in power plants the steam flow rate are usually high, this combination leads to a large equipment which the cold fluid is water in most cases.

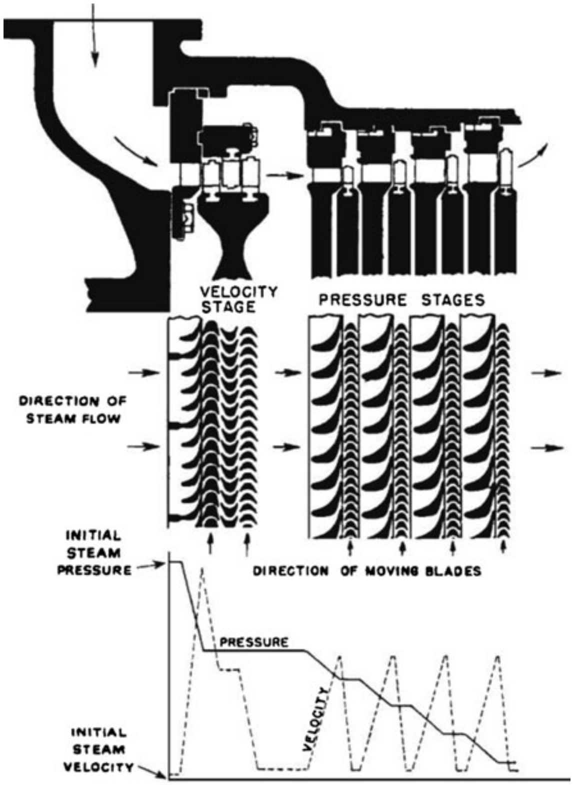


Fig. 11 The Curtis-Rateau turbine

The more frequent configuration is the surface condenser, showed in Fig. 14, where there is a metallic surface separating the condensing steam and the water. Although small the cylindrical condenser bellow shows the main parts of a condenser operating in a power plant.

One important feature is the air cooler. It is connected with the vent (air offtake) and it is just a fraction of the tube bundle, with a small tube pitch and located in a position that facilitates the non-condensable air to leave the condenser and be discarded with the help of a steam ejector.

It is included in all installations the deaerator, an equipment especially designed to remove the air from the water. Nevertheless, some air remains in a mixture with the liquid water or steam. And is inside the condenser where it separates from the steam and tends to accumulate there.

Even in small quantities, air reduces substantially the heat transfer coefficient and this can impair the condensation around the tube bundle, causing a sudden increase in the turbine back pressure.

The cooling water can be obtained from rivers, sea or recirculated water using cooling towers.

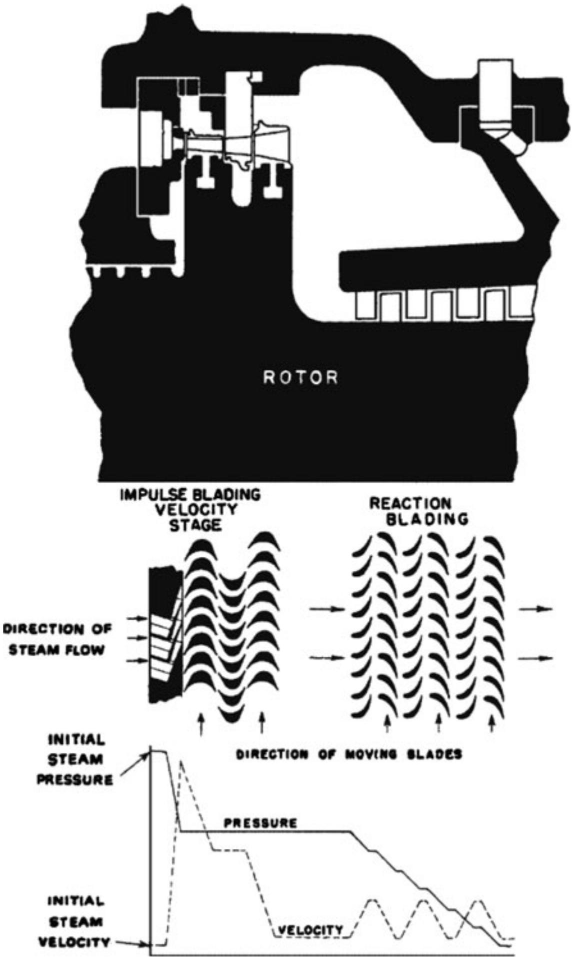


Fig. 12 A Curtis-Parson turbine

The first two options depends on the plant location and, nowadays, also costly measures to protect the river or marine environment.

The use of cooling towers reduces the water cost but it brings high capital and operational costs.

The photo presented in Fig. 15 shows a typical use of atmospheric cooling towers in a power plant.

The main heat transfer mechanism in cooling towers is the diffusion mechanism. Figure 16 shows a physical model for the energy exchange of the liquid water and the humid air.

When the water temperature is equal, in some point, to the humid air temperature, no convection heat transfer will take place. But energy is still removed from the liquid water by the diffusion of water vapor into the humid air. This last

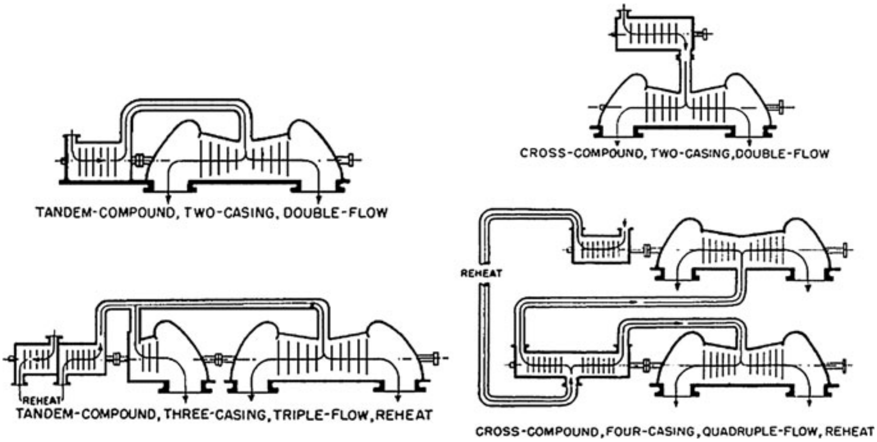
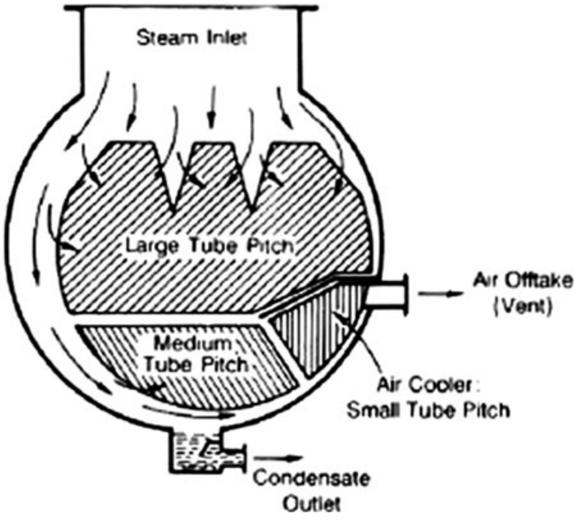


Fig. 13 Compound turbines

Fig. 14 Surface condenser

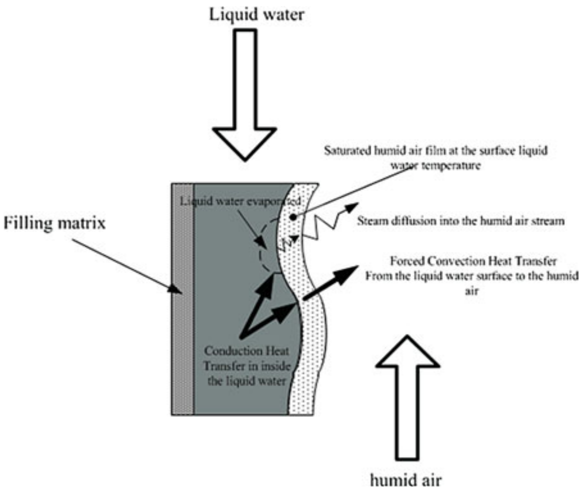


mechanism will also stop when the water vapor concentration in the humid air reaches its limit at the air temperature. The indirect measure of this concentration is the thermodynamic saturation temperature which is approximated by the wet bulb temperature. This last temperature at the tower inlet is the ultimate limit for the cooling water.

As the wet bulb temperature is usually less than dry bulb temperature the use of a cooling tower could represent an increase of the plant efficiency as the Eq. 1 indicates.

Fig. 15 Atmospheric cooling tower

Fig. 16 Heat and mass transfer from liquid water to humid air, in a cooling tower



In some places where water is rare, there is room for air cooled condensers. Figure 17 illustrates this type of condenser,

4 The Brayton Cycle

The Brayton cycle is the thermodynamic model for the gas turbine cycle. The open configuration shown in Fig. 18 is the most common presentation of this thermal engine.

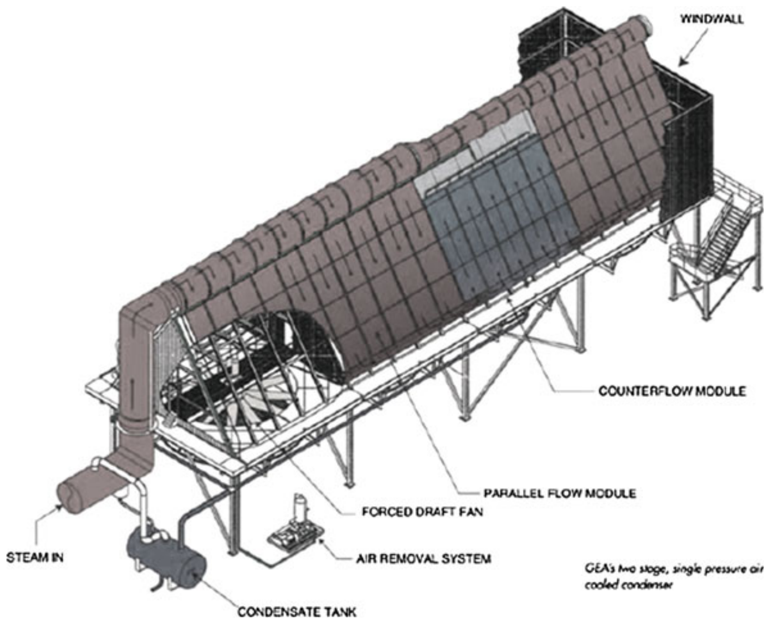
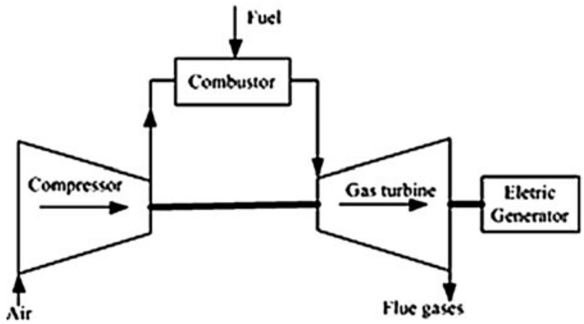


Fig. 17 Air cooled condensers (GEA heat exchangers)

Fig. 18 The open Brayton cycle



Analyzing the heat input is possible to observe a major difference with the Rankine cycle; the combustion is not external to the working fluid anymore.

Although the combustion reaction has its own irreversibility, we can imagine this cycle capable to operate with higher temperatures than the Rankine cycle. There is a potential better use of the fuel energy than we saw before. But a drawback is the use of a compressor. This component demands a high percentage of the mechanical energy produced by the gas turbine.

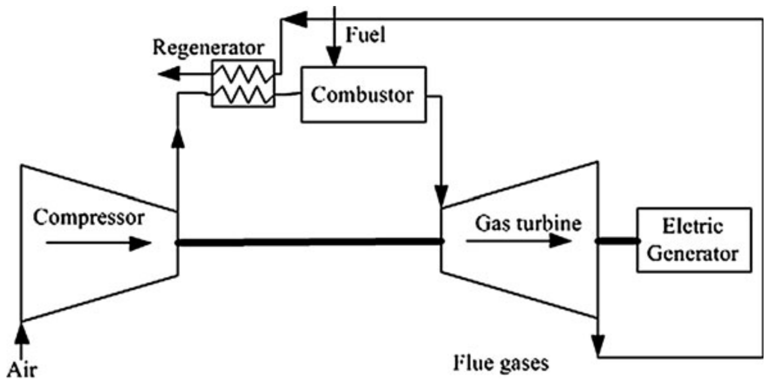


Fig. 19 Brayton cycle with a regenerator

The gas turbine is lighter and smaller than the steam cycle and this gives an enormous flexibility to the gas turbines, furthermore the gas turbine works with several fuels and has a quick starting (as low as 10 s).

There are two important categories of gas turbines:

- Industrial heavy-duty gas turbines
- Aircraft derivative gas turbines

The first of these gas turbines categories are designed to ground operation so the weight and size are not a restriction, the pressure ratio can be as high as 25:1 and the maximum turbine inlet temperature is around 1,300°C. Those cycles reach an overall thermal efficiency of 40%.

The aero derivative gas turbines are more flexible and easier to operate than the industrial ones.

The first cycle modification is the introduction of a regenerator heat exchanger, as shown in Fig. 19.

With this heat exchanger the pressure ratio could be lower reducing the compressor work. There is however, a limitation, this a gas versus gas heat exchanger, so in order to recuperate large amounts of energy, the size and the pressure drop tend to be unacceptable beyond certain power.

Another mechanism to reduce the compressor work is to cool the air while being compressed. An intercooler could do this job but this will increase the installation cost significantly.

The water injection between the low and high pressure stages will also cool the air reducing the power required by the compressor. Water is also injected in the compressor inlet and depending on the ambient temperature an increase in the net power of 8–20% is obtained combining these two injections.

There is also a possibility of a vapor injection before the combustor. This will increase the power produced in the turbine and also could control NO_x emissions.

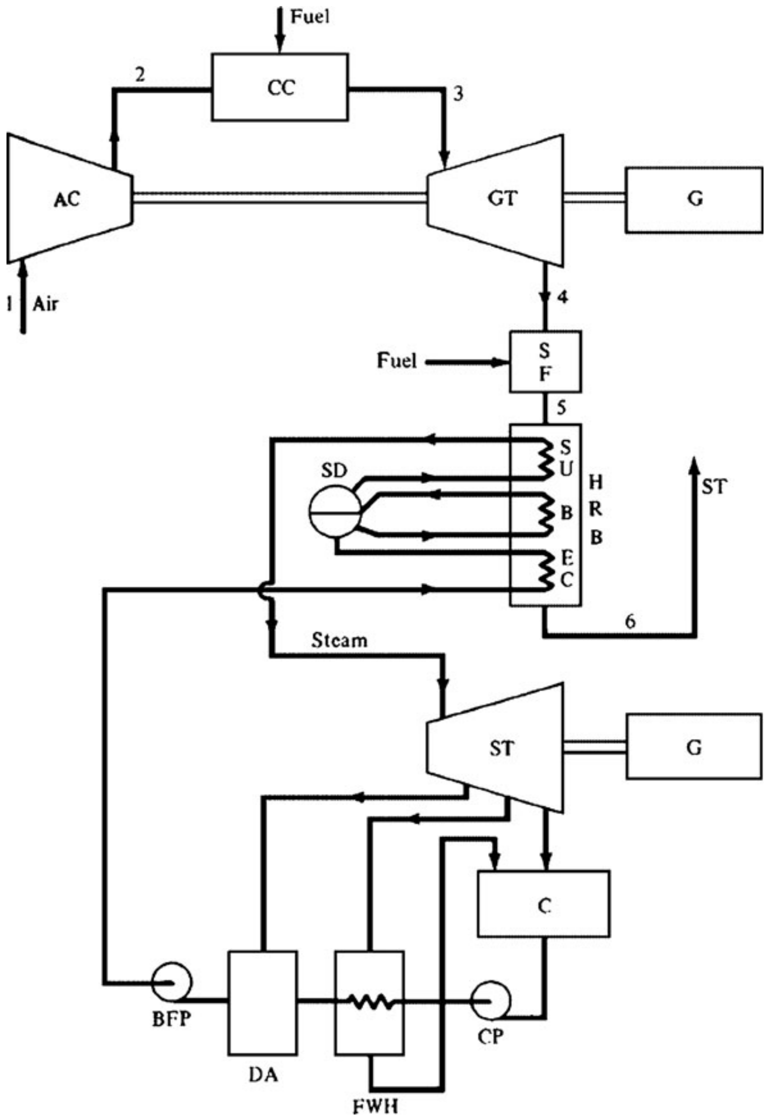


Fig. 20 The combined cycle (Power Generation Handbook Digital Engineering Library@ McGraw-Hill). Legend: *AC* Air compressor, *CC* Combustor chamber, *GT* Gas turbine, *G* Eletric generator, *SF* Supplementary fuel, *HRS* Heat recovery boiler, *SU* Superheater, *SD* Steam drum, *B* Boiler, *EC* Economizer, *ST* Stack, *ST* Steam turbine, *C* Condenser, *CP* Condenser pump, *FWH* Feed water heater, *BFP* Boiler feed pump

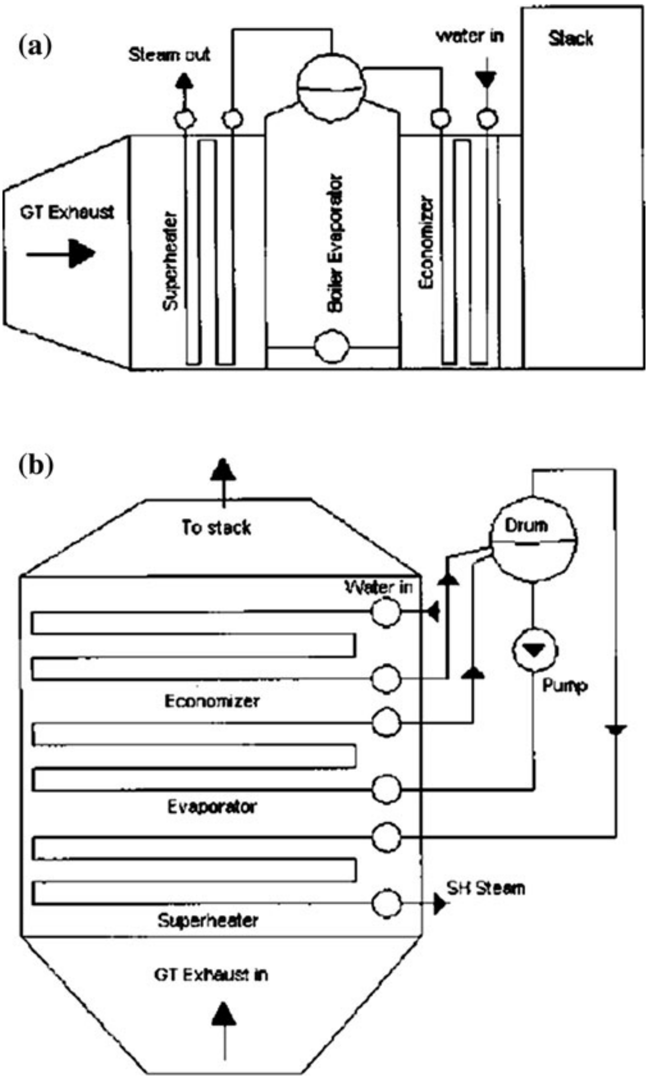


Fig. 21 HRSG configuration, (*source* Ganapathy [4])

5 The Combined Cycle

This cycle is in fact the combination of the previous cycles. It brings the ability to extract work from very temperatures (Brayton Cycle) and the capacity to produce work with a large enthalpy variation (Rankine Cycle).

The diagram presented in Fig. 20 shows a basic configuration for this cycle.

In the near future combined cycles will reach 60% of thermal efficiency, a remarkable value for this parameter.

The Heat Recovery Boiler (HRB), shown in Fig. 21, plays a crucial role in this cycle. It is a complex heat exchanger that receives the turbine exhaust gases at 540°C approximately.

Due metallurgical limitations, the gas turbine cycle uses a great amount of air in order to control the turbine inlet temperature (<1,400°C). This results in considerable amount of oxygen, ($O_2 \cong 14\%$, $H_2O \cong 6$–10%) in the exhaust gases and they can be fired with the addition of air.

Another difference in the HRBs (or HRSG Heat Recovery Heat Generator) is that the turbine exhaust gas flow, remains close to a constant, due the necessary synchronism with the electric generator. This additional firing can help to increase the steam generation in the HRB. In those boilers, the ratio of gas to steam flow varies markedly due the lower temperatures of the hot stream in contrast with traditional boilers.

With respect water circulation, those boilers have the same possibilities we have in traditional boilers, i.e. natural circulation or once-through.

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